OPERATION OF A LONG CONDUCTION TIME ELECTRON-BEAM CONTROLLED SWITCH†

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Abstract

The use of an electron beam to control the conductivity of a high pressure diffuse gas discharge has potential application as a high power repetitive opening and closing switch.[1] For some opening switch applications, the electron-beam controlled switch (EBCS) must conduct with small losses for the time it takes to energize an inductor, usually $\geq$ 1 µs. In this paper we report on the construction of a beam generator capable of 300 kV, 1 kA (average) electron beam from a cold cathode for pulse lengths that can be varied from 0.5 - 5 µs. This generator is used to provide the electron beam for driving an electron beam controlled switch in the ~ 1 µs conduction time regime. Initial results obtained with the switch system will be discussed.

Introduction

There is an interest in the application of externally controlled, high pressure, volume discharges to high power switching. The applications of particular importance involve opening switches for both single and repetitively pulsed, high power, inductive generators.[1] Such discharges have great potential for these applications because they can recover rapidly to the original highly resistive state of the gas once the external ionizing agent is removed.

Several authors[2-9] have reported on experiments and theoretical investigations in which an electron beam (e-beam) is used as the external agent to sustain the diffuse discharge. In these experiments the accelerated e-beam is injected into a chamber filled with a non-attaching base gas at 1-10 atm pressure along with a small admixture (~ 1%) of an attaching gas. The gas resistivity at any time is determined by a competition between ionization provided by the e-beam and the various recombination and attaching processes characteristic of the specific gas mixture, pressure, and applied electric field. This, along with the volume discharge property, allows the gas to return to its original nonconducting state very quickly once the source of ionization is removed. The particular advantages of this switching scheme are: 1) the intrinsic switching can be made very fast[7] (~ 1 ns), 2) there is a potential for repetitive operation at $\geq$ 10 kHz in a burst mode[7]; and 3) the switch inductance, mechanical shock, and electrode wear can be minimized because of the diffuse nature of the discharge.

Description of the Experiment

A schematic representation of the demonstration model e-beam controlled switch is shown in figure 1. It consists of a pressurized chamber containing the test gas mixture between two 25-cm diameter switch electrodes. The switch anode consists of a 70% transmitting brass screen. The e-beam enters
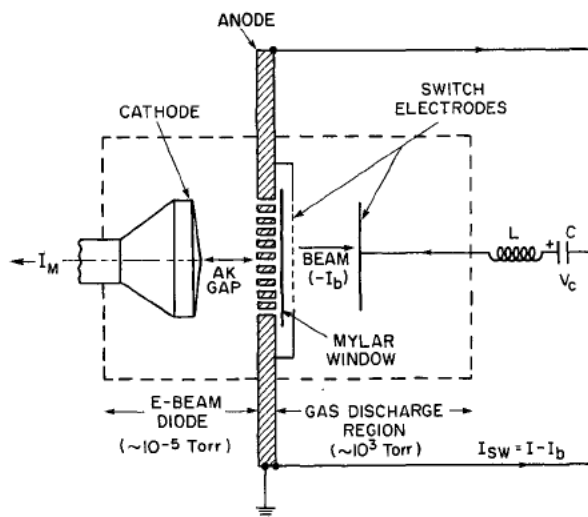

Fig. 1 Schematic representation of the experiment.

the chamber through the anode plate of the e-beam diode drilled with 0.5-cm diameter holes such that the fraction of open area was 0.68. A 5×10^{-3}-cm thick (2 mil) mylar sheet sealed the switch-to-vacuum interface. The switch was filled with various test gas mixtures at pressures from 1 - 10 atm. When the e-beam was on, current flowed in the
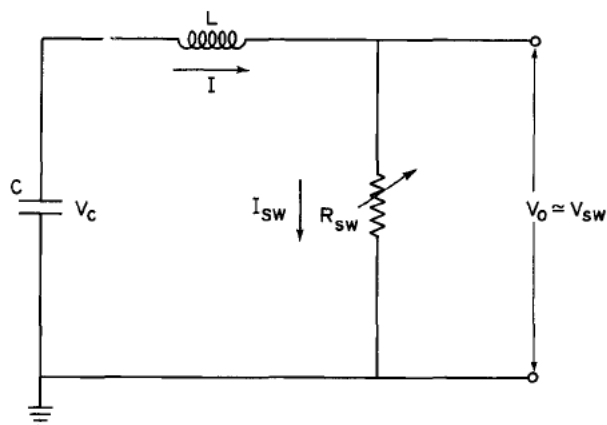

Fig. 2 Schematic of the circuit.

circuit which contained the current source C and the inductive store L as illustrated in the equivalent circuit shown in Fig. 2.

The circuit equation is

$$V_C(0) - \frac{1}{C} \int I_{SW} dt - L \frac{dI_{SW}}{dt} - I_{SW} R_{SW} = 0. \qquad (1)$$

where C is the capacitance of the capacitor used as the current source, I_{SW} is the switch current, L is the value of the storage inductance, $V_C(0)$ is the initial voltage across the capacitance C and R_{SW} is

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14. ABSTRACT
The use of an electron beam to control the conductivity of a high pressure diffuse gas discharge has potential application as a high power repetitive opening and closing switch.1 For some opening switch applications, the electron-beam controlled switch (EBCS) must conduct with small losses for the time it takes to energize an inductor, usually> 1 \JS. In this paper we report on the construction of a beam generator capable of 300 kV, 1 kA (average) electron beam from a cold cathode for pulse 1 engths that can be varied from 0.5 - 5 \lS. This generator is used to provide the electron beam for driving an electron beam controlled switch in the~ 1 \JS conduction time regime. Initial results obtained with the switch system will be discussed.

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the EBCS transient resistance. Note that in Eq. (1) we have assumed $I_{SW} \simeq I$, where $I = I_{SW} + I_b$ is the total current measured in the switch circuit. For all data shown here $I_{SW} \simeq I$. Also, in all cases the switch polarity is in such a direction as to accelerate the injected e-beam electrons. The first two terms in Eq.(1) represent the instantaneous voltage across the capacitor, V_C. The third term is the voltage across the storage inductance. The voltage across the switch is $V_{SW} = I_{SW}R_{SW}$. By making R_{SW} large very quickly, large negative values of dI_{SW}/dt can be obtained, leading to high voltage across the switch. Because we are using an open circuit as a load, the output voltage $V_O = V_{SW}$. The diagnostics used included calibrated Rogowski coils, magnetic probes, and a calibrated voltage divider.

The e-beam controlled switch was designed in accordance with previously described procedures.[1,8] The e-beam cathode consisted of a 30-cm diameter carbon felt surface which was shaped for almost uniform field emission. The A - K gap was variable from 0 - 20 cm. A 250 kV acceleration potential was maintained across the diode by a 6-stage Marx pulser. The e-beam pulse was terminated in time by a divert switch connected across the diode which it shorted when triggered. The e-beam decay time was measured to be ≤ 100 ns.
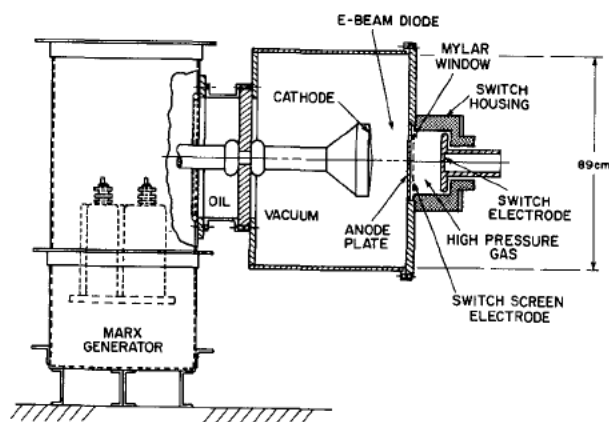

Fig. 3 Illustration of the EBOS system.

The physical arrangement of components for the electron beam controlled switch system is illustrated in Fig. 3. The six stage oil insulated Marx generator was arranged so that a switch column having a single trigger electrode could be used. UV radiation from the triggered switch illuminated the other 5 gaps and aided their breakdown. To further reduce the triggering jitter, a 100 kV pulse, which was equal to a factor of 5 overvoltage, was applied to the trigger electrode.

To convert the conventional Marx output to a pulse having an adjustable time duration and constant voltage, two additional switches were used. The first was an untriggered output switch which connected the Marx to the e-beam diode. It isolated the diode from the Marx during the period of slow voltage erection, then broke down at a pre-selected high voltage. This resulted in a fast rise (~ 100 ns) of the Marx output voltage. The second, called a divert switch, determined the time duration of the voltage pulse that was applied to the e-beam diode.

On command, after a pre-selected delay, the divert switch, which connected the Marx output to ground, was triggered. When conducting, it shorted the e-beam diode, cutting off the delivery of electrons to the e-beam controlled switch. The decay time for the Marx output voltage was measured to be ≤ 100 ns. To reduce the jitter of the pulse length to a negligible interval, a slight flow of high pressure N_2 was maintained in the switch. Specific details of the entire system design can be found elsewhere.[10]

Research Results

The gas mixture 1% C_2F_6 - CH_4 has been suggested[11] as having good qualities as a mixture for e-beam controlled switches, and has been chosen as a first gas to study in the e-beam controlled switch.
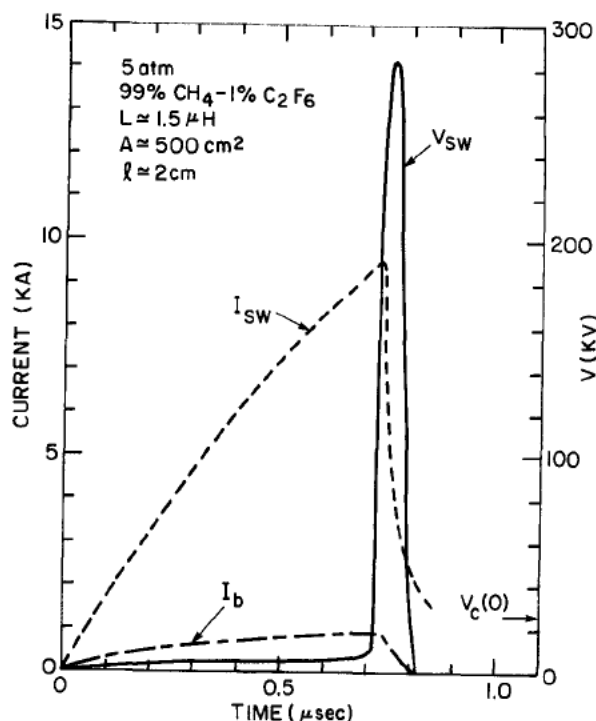

Fig. 4 Switch performance curves.

The graphs in figure 4 show the results of operating the demonstration model e-beam controlled switch, previously described, as a component of an inductive storage system. The switch, which had an area of 500 cm^2 and a length of 2 cm was filled with 1% C_2F_6 + 99% CH_4 (0.03% impurity, by manufacturer's specification) at a pressure of 5 atm. The initial voltage on the energy storage capacitor was $V_C(0) = 26$ kV.

The e-beam current I_b, plotted as a function of time in µs, reached a peak of 0.95 kA, then fell to zero in 80 ns, after the divert switch was closed. The switch conduction current I_{SW} traced a curve proportional to I_b, but was larger by a factor of 10; it reached a peak value of 9.6 kA and fell rapidly when the divert switch closed. As I_{SW} fell, an inductive voltage pulse equal to L dI_{SW}/dt was generated. When these values and others were

ubstituted into Eq. 1, the voltage V_{SW} across the switch as a function of time was calculated. V_{SW} is also plotted in the figure. It shows a peak voltage of 280 kV and a FWHM of 60 ns.

The mechanisms involved in the opening phase of switch operation can be illustrated with the aid of curves presented in Fig. 5. The data are plotted on a slow time base in Fig. 5(a) to show the entire charging pulse and on an expanded time scale in Fig. 5(b) centered on the time of peak voltage generation across the switch. This "expanded view" better
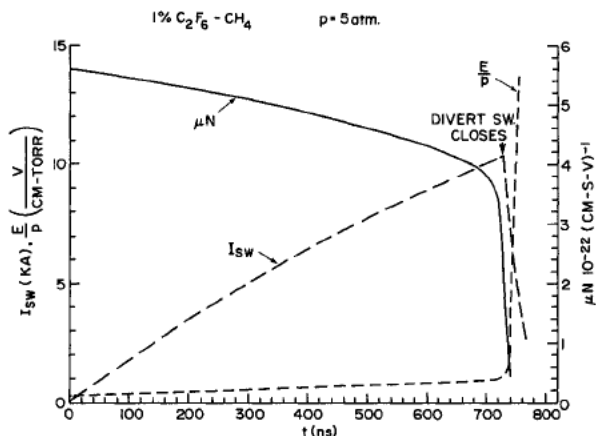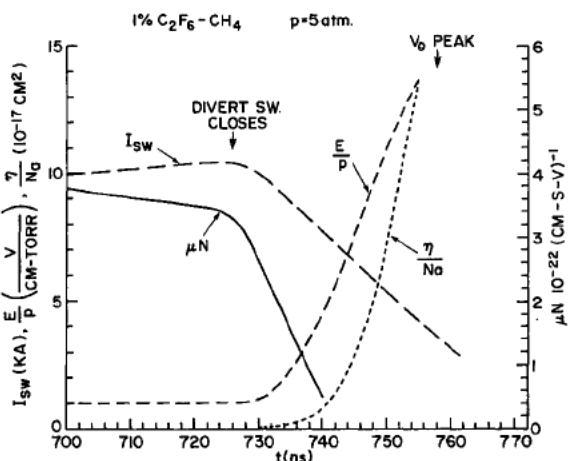

Fig. 5(a) Slow time base.

Fig. 5(b) Expanded time scale centered on time of peak voltage. (n/Na obtained from Ref. 11)

Fig. 5 Illustration of switch opening.

phenomena. The expanded time interval is indicated in the figure.

As data on the slow scale in Fig. 5(a) indicates, during the time of current increase from zero to maximum at 730 ns, E/P rises slowly from 0.4 to 1.0 V/cm-torr. This is a favorable range of E/P for the mixer gas CH_4 and it results in the normalized electron mobility remaining high during this period, which is desirable.

As indicated on the expanded time scale in Fig. 5(b), when the divert switch closes, causing e-beam current, and therefore the switch current I_{sw} to

fall, E/P increases rapidly. When E/P is in the range of 1-3 V/cm-torr, while time varies from 730 to 740 ns, the normalized electron mobility[12] for CH_4 falls rapidly from 3.5×10^{23} to $0.8\times10^{+23}$ $(cm-s-V)^{-1}$. During this period, the normalized attachment coefficient η/N_a for the gas mixture[12] $1\%C_2F_6 - CH_4$ changes from ~ 0 to $0.2\times10^{-17}cm^2$, a relatively small amount. But as the switch current I_{sw} continues to fall during the time interval between 740 and 754 ns and E/P increases above 3 V/cm-torr, the attachment coefficient η/Na rises rapidly by a factor of ~ 48 from 0.2×10 to $9.5\times10^{-17}cm^2$. When η/N_a was at its maximum value E/P was ~ 14. The collective effect of the decline in μN, and the increase in η/N_a is to make the current fall-time shorter and therefore, increase the output voltage $V_0 \propto L \Delta I_{sw}/\Delta t$. Note that higher voltage makes η/N_a larger, which in turn leads to higher voltage. This example is only an illustration of switch performance that results from the mixture of one attaching gas C_2F_6, with the non-attaching gas CH_4. It is likely that switch operation could be tailored to match a desired performance specification by varying the gas mixture and the operating conditions. Thus one might optimize output voltage, output current, current gain, switch resistance, etc., for a given application.

Conclusions

We have demonstrated that an electron-beam controlled diffuse discharge can be successfully employed as the opening switch in a high-power, inductive store system. In the present system an output voltage pulse of 280 kV and 60 ns duration was generated after charging an inductor to 10 kA in ~ 1 μs. This performance was obtained using an e-beam current of 1 kA injected into a gas mixture of $1\% C_2F_6 + 99\% CH_4$.

Although switch performance was both predictable and reproducible, limited resources prevented us from optimizing this performance. Considerable improvement in performance could be obtained by careful selection of the circuit parameters and gas mixture and by reducing the e-beam turn-off time to below 100 ns.

Acknowledgements

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